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D. H. Kalantar, A. M. Allen, F. Gregori, B. Kad, M. Kumar, K. T. Lorenz, A. Loveridge, M. A. Meyers, S. Pollaine, B. A. Remington, J. S. Wark

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LASER DRIVEN HIGH PRESSURE, HIGH STRAIN-RATE MATERIALS EXPERIMENTS*

D. H. Kalantar[1], A. M. Allen[2], F. Gregori[3], B. Kad[3], M. Kumar[1], K. T. Lorenz[1], A. Loveridge[1], M. A. Meyers[3], S. Pollaine[1], B. A. Remington[1], J. S. Wark[2]

Lawrence Livermore National Laboratory, Livermore CA 94550
Clarendon Laboratory, University of Oxford, Parks Roord, OX1 3PU, UK
University of California at San Diego, La Jolla, California, 92093

Laser-based experiments are being developed to study the response of solids under high pressure loading. Diagnostic techniques that have been applied include dynamic x-ray diffraction, VISAR wave profile measurements, and post-shock recovery and analysis. These techniques are presented with some results from shocked Si, Al, and Cu experiments.

INTRODUCTION

When a material is shock compressed at a low pressure, it typically responds by elastically deforming. At a pressure above the Hugoniot Elastic Limit, it deforms plastically. Plastic deformation is often characterized by a semi-emperical model such as the Steinberg-Guinan constitutive model [1]. These models have been developed and fit to data that was recorded at low strain rates, such as obtained with a gas gun. They do not describe the microscopic physics that occurs in order for that plastic deformation to take place.

When the solid undergoes deformation at high pressure, stresses that occur at the lattice level result in the generation and subsequent propagation of dislocations [2, 3], It is this rearrangement of the lattice structure that is plastic material flow. In order to study the detailed response of a material to shock loading, it is important to study the response of the lattice itself.

We have performed a series of experiments using the Nova and OMEGA lasers to study the deformation of single crystals using the technique of *in situ* dynamic x-ray diffraction [4-6]. We present a some results from this technique to study lattice deformation, and we describe additional measurements using VISAR and post-shock recovery to support the detailed understanding of shocked solids.

DYNAMIC DIFFRACTION

X-ray Bragg diffraction provides a direct, time-resolved measurement of the $2d$ lattice spacing of a crystal structure. The x-rays scatter from the atoms in the lattice and constructively interfere when the angle of incidence with respect to the lattice planes satisfies the Bragg diffraction condition:

$$n\lambda = 2d \times \sin(\Theta)$$

The x-rays are diffracted at an angle Θ equal to the incident angle (with respect to the lattice planes).

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This technique of x-ray diffraction is applied to study a cubic lattice by selecting the x-ray wavelength so that the Bragg condition is satisfied at approximately 45°. Then, by placing the x-ray source in close proximity with the crystal, we are able to record x-rays diffracted from planes both parallel and orthogonal to the shock direction (Fugure 1).

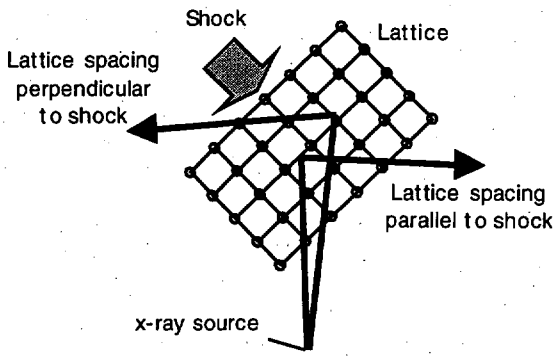
When the lattice udergoes a deformation due to shock compression, the lattice compresses and the spacing decreases. The Bragg diffraction condition is then met at a different angle corresponding to the new lattice spacing. Provided that the x-ray source is sufficiently close to the lattice so as to be incident at a range of angles, the change in lattice spacing is observed as a shift in the Bragg diffraction angle

By using multi-keV x-rays for diffraction, we probe a depth of up to several 10s of μm in the crystal. Therefore, as the crystal is shock compressed, the diffraction signal consists of x-rays diffracted by a range of lattice spacings simultaneously. A time-resolved record of the compression in the crystal is recorded using an x-ray streak camera.

This technique of x-ray diffraction is demonstrated with a shocked Si crystal. In these experiments, 8 beams of Nova were used to create a nearly Planckian radiation drive inside a cylindrical gold hohlraum. The radiation temperature ramped up to approximately 40 eV. [7-9]

A 40 μm thick single crystal of Si was located over a hole in the side of this gold hohlraum. This crystal was oriented with the [100] planes parallel to the surface. The x-ray drive ablatively launched a shock in the Si.

FIGURE 1: Setup for simultaneous diffraction from orthogonal lattice planes parallel and perpendicular to the shock propagation direction.



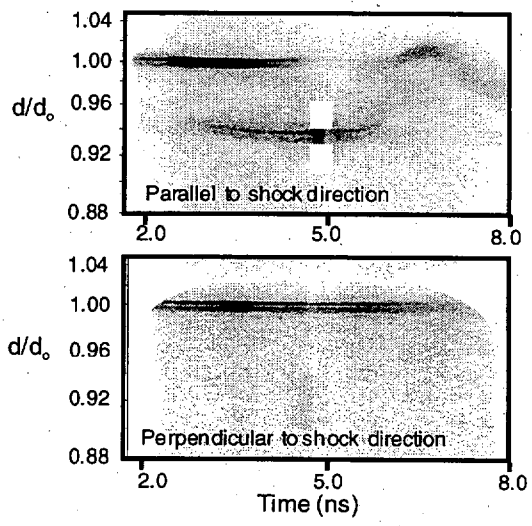
An Fe foil was placed in close proximity to the Si crystal to provide the source of x-rays for diffraction. Two beams of Nova heated the foil to create 1.85 Å He-like Fe spectral emission. These x-rays diffracted from both the [400] and [040] lattice planes with a Bragg angle of 42.95°.

As the Si was compressed, the shift in the Bragg diffracted x-rays was recorded on both static x-ray film and an x-ray streak camera. The results are shown in Figure 2. In this experiment, the peak pressure ramped up in time to over 200 kbar, but it reached only approximately 120 kbar at the free surface before the shock breakout and subsequent release occurred. The 2d lattice spacing is compressed by approximately 6% parallel to the shock propagation direction ([400] planes, and no compression is observed for the [040] planes orthogonal to the shock direction.

VISAR WAVE PROFILE MEASUREMENT

The dynamic diffraction technique provides information on the lattice level response of a solid to shock loading. This is related to the bulk material response with a conventional wave profile measurement. We have used a VISAR system at OMEGA and also at Janus to record wave breakout profiles in solid materials.

FIGURE 2: Time-resolved diffraction data from orthogonal lattice planes of Si.



Results from one such experiment are shown in Figure 3. Here, a 195 μm thick sample of rolled Al-6061 was shock compressed by direct laser irradiation using a 3.5 ns laser pulse with peak intensity of approximately $2x10^{11}$ W/cm^2. This laser pulse launched a strong shock with an initial strength of approximately 150 kbar. The shock decays during passage through the foil, and it breaks out with a peak pressure of about 40 kbar.

The wave breakout was calculated both with impedance matching LiF and with a free surface. The material parameters for this Al were evaluated based on the fit of the rising portion portion of the wave breakout profile. Specifically, we use the timing of the elastic wave, timing of the plastic wave, and amplitude of the rear surface velocity due to each of the elastic and plastic waves to fit the bulk modulus, shear modulus, and yield strength. For this Al-6061 foil, we obtained best fit values of shown in Table 1. These are compared with the nominal Al-6061 values obtained from Steinberg [10]. The degree that these values fit the rising portion of the wave profile is illustrated in Figure 3 where we have overlaid the simulation with the measured wave profiles. The simulated profiles match the rising portion of the wave profiles.

FIGURE 3: VISAR trace and analyzed wave breakout for a 195 μm thick Al-6061 foil.

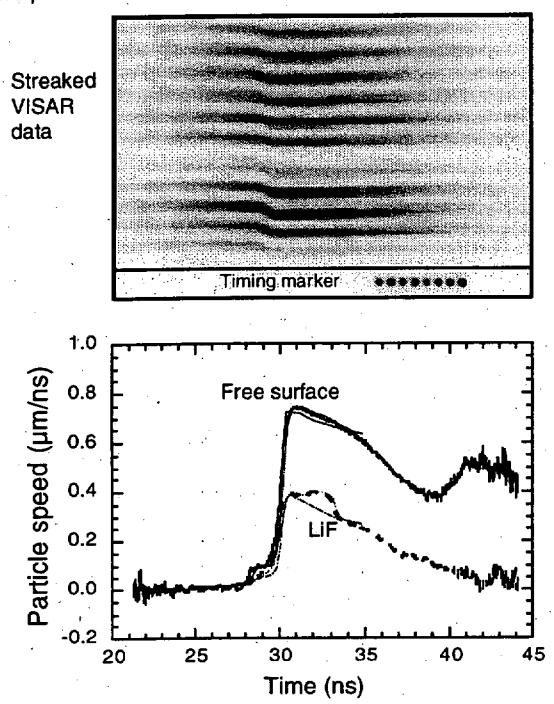


TABLE 1: Measured material parameters for Al-6061 from laser experiments compared to nominal values.

Parameter	Measurement	Nominal
Shear modulus	320 kbar	276 kbar
Bulk modulus	790 kbar	742 kbar
Yield strength	4.3 kbar	2.9 kbar

SAMPLE RECOVERY

When a solid material experiences shock loading at pressures above the Hugonoit Elastic Limit, it deforms plastically. This occurs by the generation and propagation of dislocations in the lattice. Following shock loading, the material releases, and some residual damage remains. This damage may vary due to parameters such as shock pressure and strain rate.

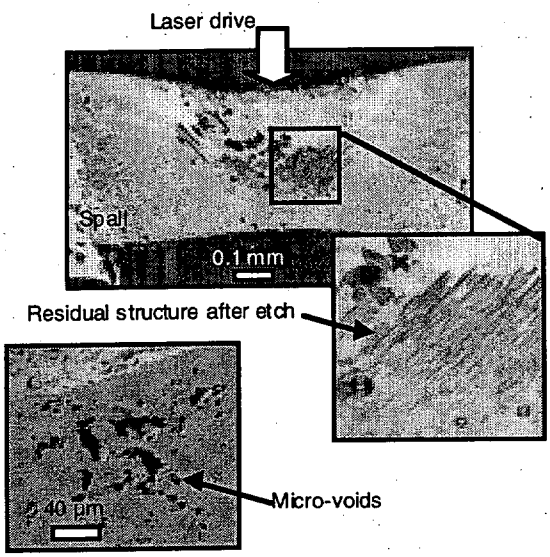
We have recovered samples of single and poly-crystal crystal Cu that were shock loaded by direct laser irradiation. These samples were 0.5 and 1.0 mm thick with a (100) lattice orientation. A short duration laser pulse was used to launch the initial high pressure loading wave that decayed as it propagated through the sample. This was 1-3.5 ns for the different experiments.

The recovered samples have been analyzed by optical and transmission electron microscopy. Samples of the defect structures visible are shown in Figure 4. There is void formation, and spall. The residual microscopic damage from two separate samples is shown in Figure 5. These single crystal samples of Cu were sample shocked with peak pressures of approximately 400 kbar and 130 kbar. The lower pressure sample shows a high density of dislocations. The higher pressure sample shows a cell structure with regions of micro-twinning. These results are discussed in detail by Meyers *et al* [11]

SUMMARY

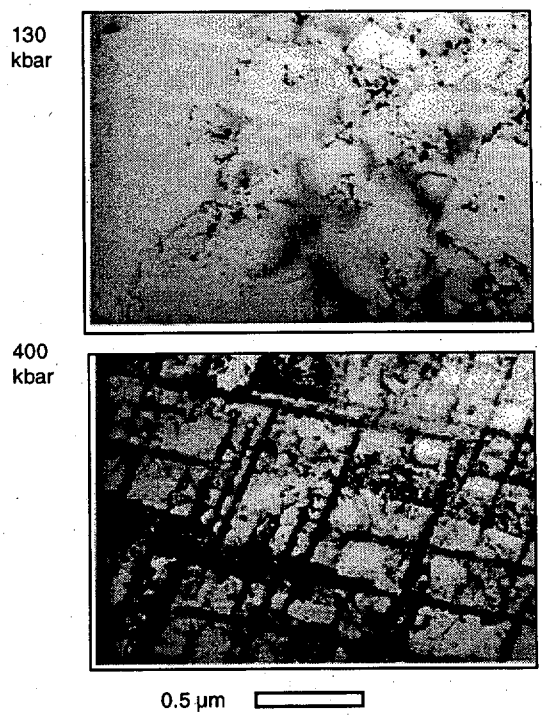
We are using intense lasers to shock load materials in order to study the shock response at high pressure and high strain rate. Dynamic x-ray diffraction is used to probe the lattice reponse

FIGURE 5: Recovered samples of Cu show void formation and spall resulting from the high pressure loading.



directly. The residual microstructure is evaluated with electron microscopy of the recovered samples, and VISAR wave profile measurements provide a calibration for the shock pressures and a coupling to conventional shock experiments.

FIGURE 5: TEM images from two samples of single crystal Cu shocked with a peak pressure of 130 kbar and 400 kbar.



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University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551